SRF LINAC COMMISSIONING

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Outline

- **Dynamics of RF-drive/cavity/beam system.**
- **Description of the Simulations**
- **SC Linac commissioning procedure.**
- **Simulation of 6 and 12 SC cavities with beam.**

The TRANS code calculates the dynamics of a RF-drive/cavity/beam system.

- The Basic Formalism Used in the TRANS Code.
  - Four factors that affect amplitude and phase of an RF mode in an accelerating cavity.
    - $e^{-w_q \cdot \Delta t/2Q_q}$ Which represent losses in the cavity.
    - Frequency of the qth mode: $e^{i(w_q - w)\Delta t}$
    - The external RF drive.
    - The beam induced voltage.

Losses in the cavity.

- $\vec{a}(q,t)$ is a complex number that represents the amplitude and phase of the qth mode at time *t*. The phase is with respect to the to the RF reference at frequency *freq*. The angular frequency.

$$w = 2 \cdot p \cdot freq$$

- $e^{-w_q \cdot \Delta t / 2Q_q}$ represent losses in the cavity. w_q is the angular frequency and Q_q is the quality factor of the of the qth mode. Δt is a small increment of time.

- In this simulation with Q_q equal to about 1.0 x^{10} the losses in the cavity are negligible. However, It is used in the definition of b the coupling to the RF drive. Q_{loaded} is the *Q* with the RF drive.

$$\boxed{b = \frac{Q_0}{Q_{loaded}} - 1}$$

Q_0 is the unloaded Q of the accelerating mode.

Frequency of the q^{th} mode.

- Frequency of the q^{th} mode: $e^{i\left(w_q - w\right)\Delta t}$
- Each mode rotates in the complex plane with respect to the drive frequency.
- For small Δt and small frequency difference, this term is ~1. Which means that the phase of the RF fields do not change very much.
- This make it possible to measure the phase of the beam accurately with short high current beam pulses.

The external RF drive.

- $\vec{pf}$ is a complex number that represents the amplitude and phase of RF drive. $\vec{pt}$ is a complex number that represents the amplitude and phase of the RF transmitted out of cavity through the coupling to the RF drive line. *b* is the coupling factor for the desired mode *n*.
- $\vec{pt} = \sum_{q=0}^{N} \vec{a}(q,t) \cdot \mathrm{X}(q, N_d) \cdot \sqrt{b} \cdot$
- Where N_d is the cell number that the wave guide is coupled to and N is the total number of cells.
- $\mathrm{X}(q,m)$ is normalized amplitude in cell *m* for the qth mode.

Computer code LOOP calculates the phase and amplitude of the RF fields.

- The values of $\mathrm{X}(q,m)$ are calculated by the computer code LOOP which is based on coupled RLC loops.
  – These represent the amplitude and phase of the RF field in each cavity for every mode in the coupled cavity system. (Every mode in the accelerating pass band.)
- The net result of the forward RF power and the reflected power on the qth mode is:
- $\vec{p}(q) = \left(2 \cdot p\vec{f} - p\vec{t}\right) \cdot \sqrt{b} \cdot \mathrm{X}(q, Nd) / \mathrm{X}(n, Nd)$

The beam induced voltage.

- $\vec{B}(m)$ is a complex number that represents the amplitude and phase of the beam induced voltage in cell *m*.
- The effect on the q[th] mode is: $\sum_{m=0}^{N} \vec{B}(m) \cdot \Delta t \cdot \mathrm{X}(q,m) / N$
- $\vec{B}(m)$ is calculated in PARMELA by summing the effect of each particle passing through the electric fields E_z of the cavity. V_z is the velocity of the particle at position *z.*

$$\vec{B}(m) = \frac{\sum\limits_{\text{particles}} \int\limits_{z=0}^{z=L} V_z \cdot \text{charge} \cdot E_z(z) \cdot e^{i(w \cdot z / V_z + j_0)} dt}{\int\limits_0^L E_z(z) dz}$$

; f_0 is the phase of the RF fields.

The net result of the 4 factors.

- With the values of $\vec{a}(q,t)$ determined the rest of the calculations can be performed. The reflected power can be calculated. Periodically PARMELA simulations are performed to calculate the performance of the accelerator and update $\vec{B}(m)$:

$$\vec{a}(q,t+\Delta t)=\vec{a}(q,t)\cdot e^{\left\{-w_q/2\cdot Q_q+i\cdot(w_q-w)\right\}\cdot\Delta t}$$

$$+\left\{\vec{P}(q)+\sum_{m=0}^{N}\vec{B}(m)\cdot \mathrm{X}(q,m)/N\right\}\cdot\Delta t$$

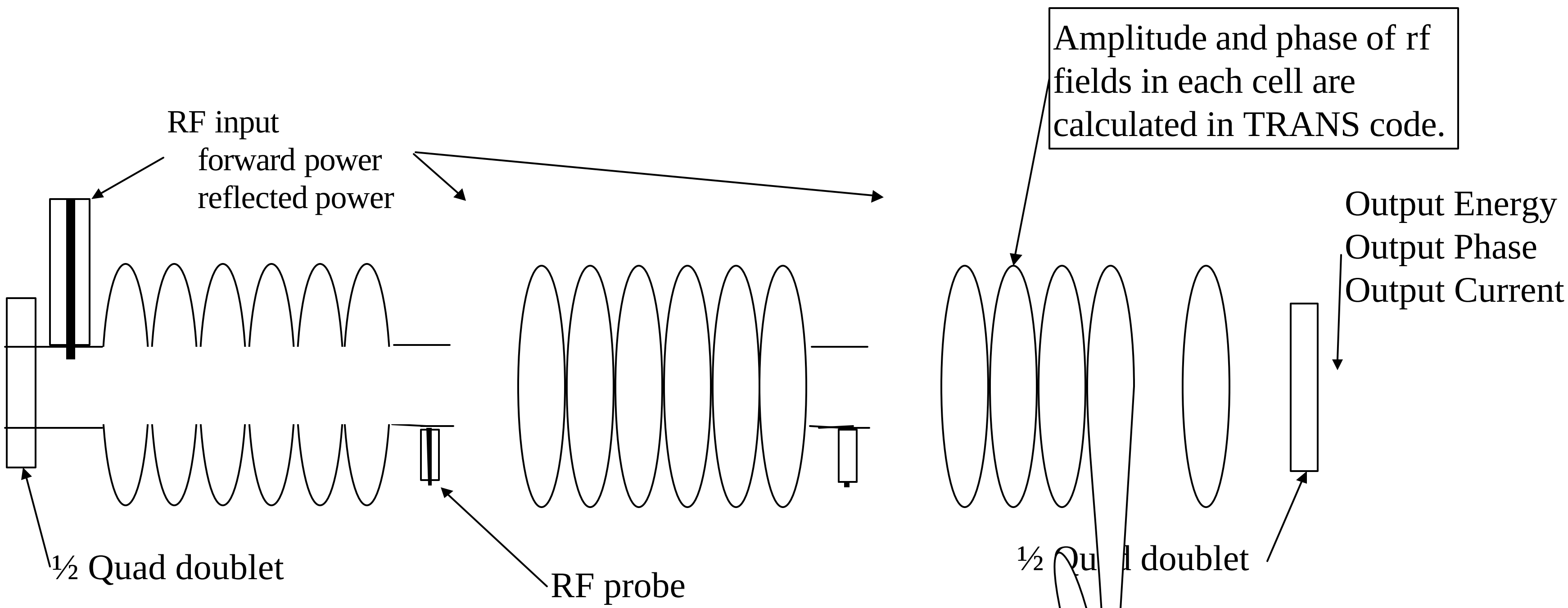
$$\Delta t=\frac{1}{freq\cdot NT} \qquad \text{where } NT=1 \text{ if } \frac{w_q-w}{freq}\le 0.025p$$

$$\text{and} \qquad NT=\mathrm{INT}\left(\frac{\frac{w_q-w}{freq}}{0.025p}\right)+1$$

Summary of TRANS formalism.

- Four items effect the fields in an accelerating cavity. They are:
  - The resonate frequency.
  - The cavity losses (in SC cavities the losses are negligible.)
  - The external Drive. (This has two parts the forward power and the transmitted power. The later provides the external Q.)
  - The beam drive. (This can be calculated quite accurately because the field distribution that is given by the SUPERFISH code is very accurate. PARMELA integrates the beam through the field distribution yielding an absolute value of the beam drive.
- **PARMELA** is an **<u>integral</u>** part of **TRANS**. It transports the beam multiple times through the part of the accelerator simulated by TRANS. The evolution of the beam pulse is thereby simulated.
  - TRANS provides PARMELA with the phase and amplitude of the field in the accelerating cells. PARMELA returns the beam drive.

Sketch of 3 cavity cryomodule.



BEAM

Procedure to commission SC Linac.

- Calibrate RF pickup probes of first cavity.
  - Use beam to excite cavity. Compare with Calculations (RF off.)
    - Amplitude and phase of cavity are set. Phase of cavity excited with beam is ± 180 - ϕ_s of required phase. (Add ± 180 + ϕ_s)
    - ϕ_s is typically -23° to -30°.
- Set amplitude and phase setpoints of first cavity and turn on RF.
- Calibrate RF pickup probes of next cavity.
- Set amplitude and phase setpoints of next cavity. Turn on RF.
- Repeat previous steps until all cavities are set.
- Periodically check beam energy with time-of-flight measurements.

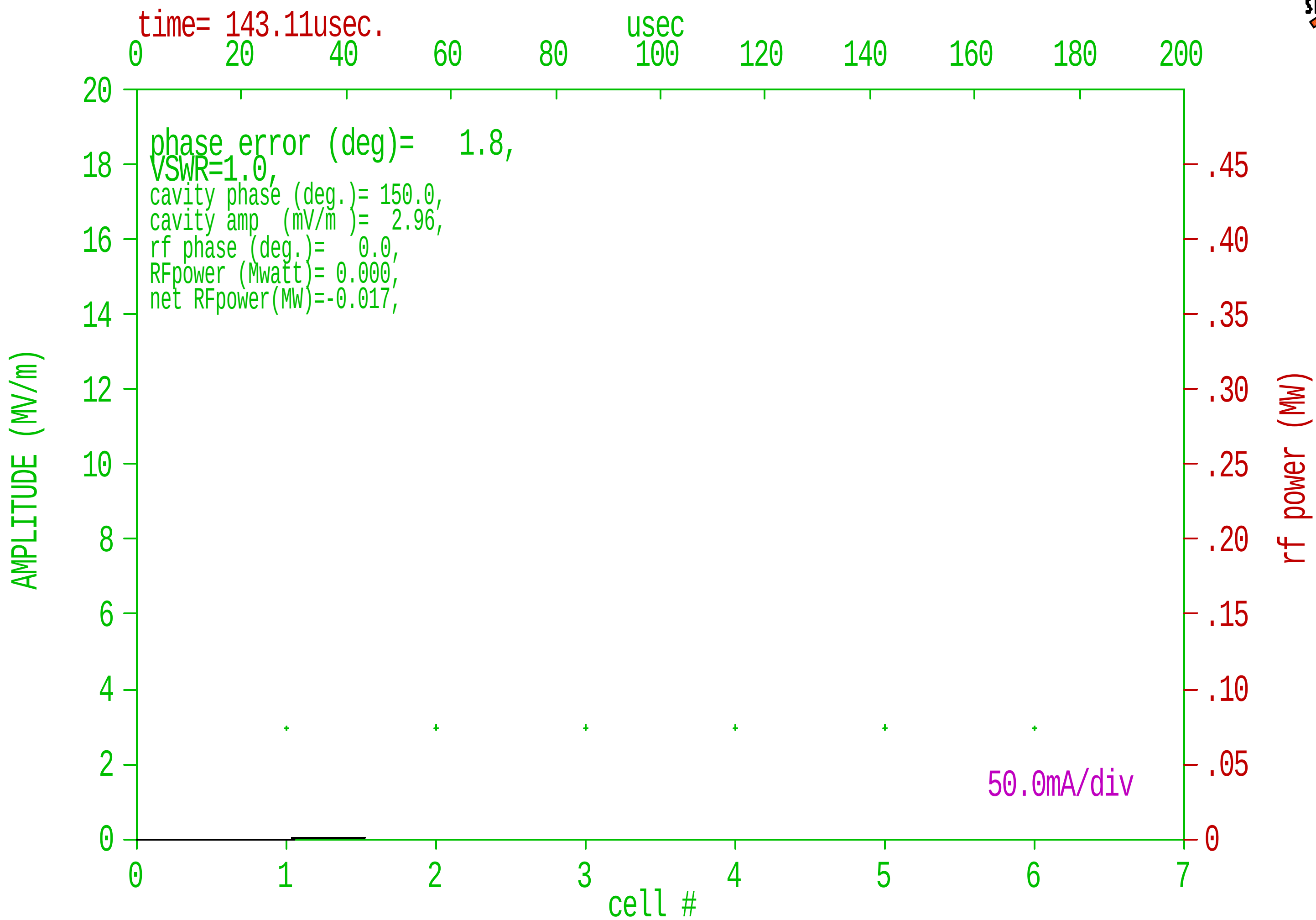
Beam requirements for commissioning.

- Beam is transported, without acceleration, through SC Linac to beam dump with negligible beam loss.
- All cavities downstream of cavity under test detuned enough to not be excited significantly by beam.
- Beam current is ~50 mA peak. Pulsing is optional. Calibration procedure works better without pulsing if ok with NC Linac.
- Beam pulse length of 100 - 150 μsec. Available.
- Low Level RF system capable of measuring amplitude and phase of cavity accurately. Then accurately setting phase setpoint $180^\circ + \phi_s$ from beam phase measured with cavity.

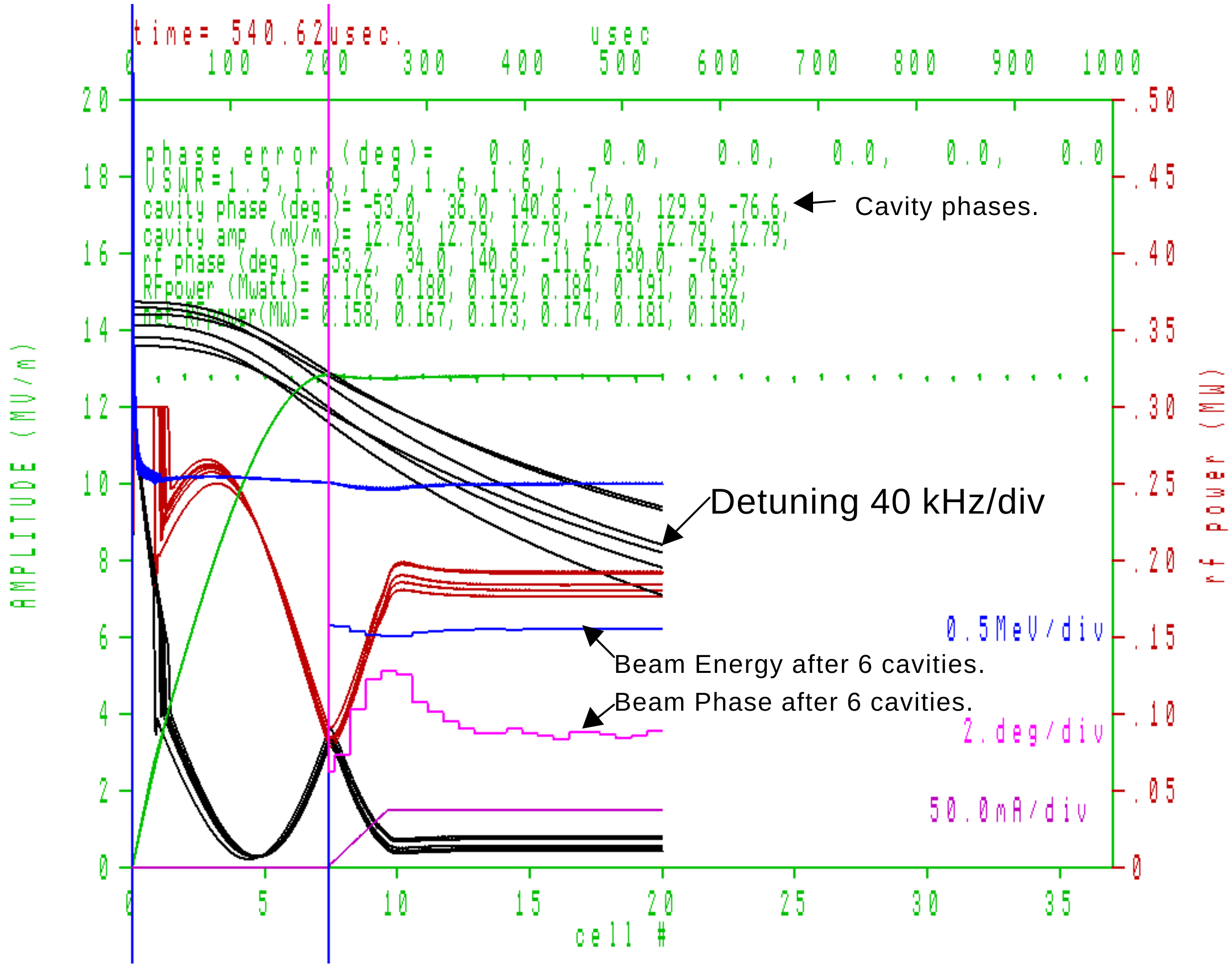
More basic assumptions or requirements.

- We can tune the SNS SC cavities to 805 MHz about +/- 30 Hz.
- The master clock has very little phase noise.
- The RF phase reference line is stable.
- The beam pulses are reasonable reproducible and that we can measure the current accurately.
- The beam has small phase error or that it can be averaged over several pulses to reduce this source of phase error to about 1°.

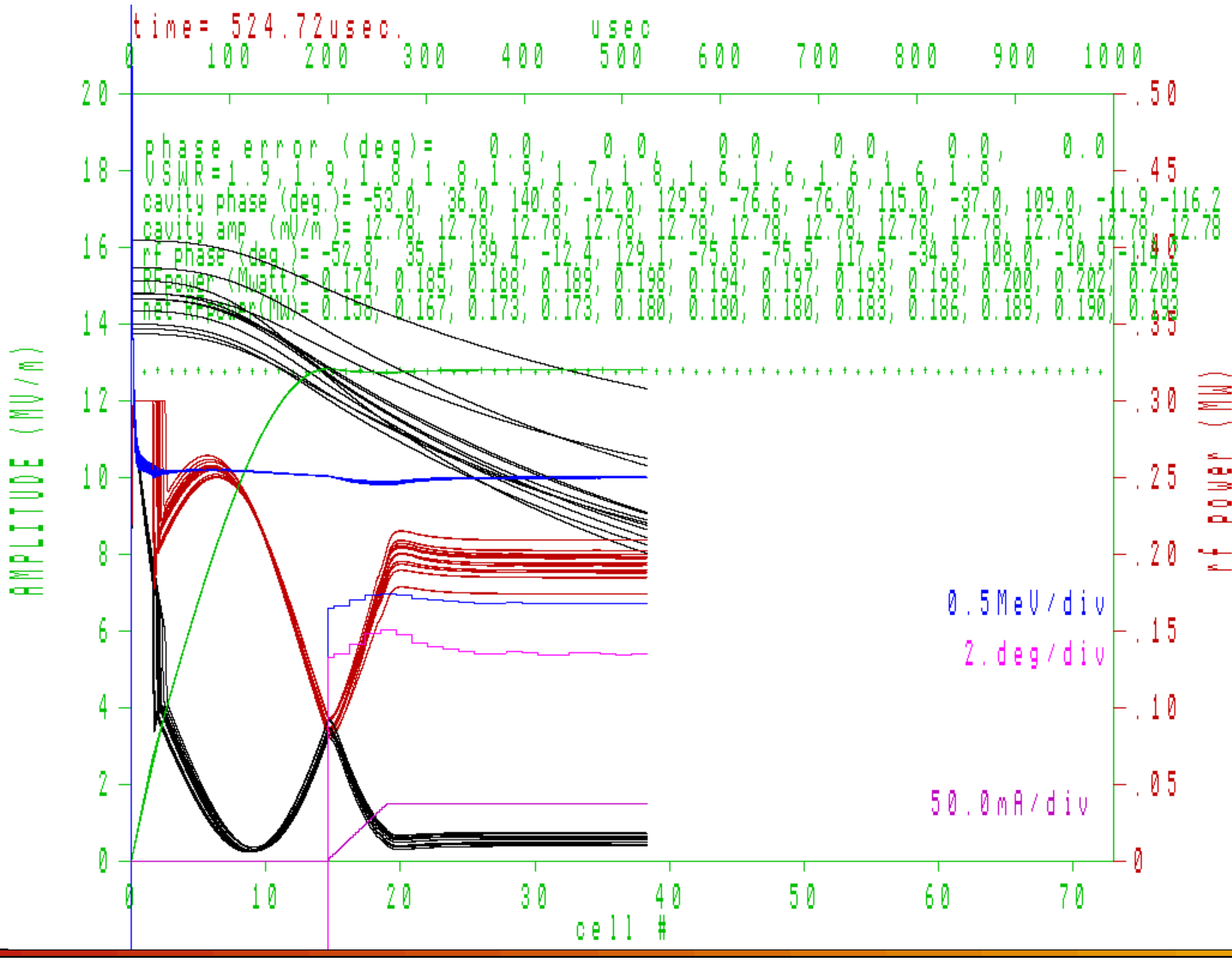
Example of beam exciting cavity.



Results of using commissioning procedure on first 6 SC cavities.



A 12-Cavity TRANS Simulation



List of parameters and errors in the 12–cavity simulation using TRANS.

- Unload Q= 1×10^{10}.
- External Q = 500,000 (+125,000, -83,000); (β= $2\times10^4 \pm 4\times10^3$).
- Resonant frequency +300 Hz (805 MHz)
- Microphonics = ± 60 Hz (random).
- Lorentz Force Detuning (K=2±1) (τ_m=400 ± 200 μsec.)
  - ~200 Hz when fully developed.
- Maximum available klystron power= 300 kW.
- First section of SC Linac. β = 0.61 cavities.
- Amplitude setpoint = 12.79 MV/m (Average accelerating field)
- Phase setpoints derived from commissioning procedure.

Summary

- Commissioning procedure tested with the code TRANS appears to work.
- Procedure previously tested successfully through 36 accelerating cavities. Only 6 and 12 cavities shown above for clarity.